The Recent Progress and State-of-art applications for Ultraviolet Photodetectors

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Abstract. Contemporarily, ultraviolet photodetectors have already been successfully applied in many advanced areas, including astronomy, disaster forecasting, fire alarm, marine oil pollution monitoring, biomedical and more. Nowadays, many researchers are focusing on developing the wide bandgap UV photodetectors which possess advantages in fast response speed, high sensitivity, self-power, etc. This paper will discuss principle, types, and component of ultraviolet photodetectors based on information retrieval and literature analysis. Specifically, vacuum UV detectors, solid-state UV detectors and wide bandgap UV photodetectors are demonstrated. According to the analysis, wide bandgap UV photodetectors have better performance in multiple properties but still be limited with several drawbacks, included material problems and design issues. Once the material problems and design issues could be overcome, they could replace the traditional UV photodetectors rapidly, which are able to benefit more relevant areas in both military and civilization. These results shed light on guiding further exploration in UV photodetectors current.

Keywords: Ultraviolet photodetectors, Photomultiplier, Flame detector, Radiation detector.

1. Introduction

In general, the wavelength ranges from 10nm to ~400nm of the electromagnetic wave is called ultraviolet light, which is invisible for humans' eyes (also known as the visible-blind band). The wavelengths below 200nm are only transporting in vacuum UV region, which are called UVD and the visible wavelength, transporting in the air ranges from 200nm to ~400nm [1]. According to the International Commission on Illumination (CIE), this spectrum can be segmented to three bands. The band with the wavelength ranges from 320nm to ~400nm is referred to UVA that has ability to penetrate the clouds and glasses to get to the ground. A large amount of UVA can reach directly the skin fiber cortex and destroy the elastic fibers and collagen fibers, resulting to darken the skin. In 2009, the scholars from Germany and Italy had found that the astaxanthin can effectively eliminate the damage brought by UVA to the skin [2]. The band with the wavelength ranges from 280nm to ~320nm is known as UVB. It has medium penetration, which means that most of the wavelengths in this zone are absorbed by the ozone sphere and only less than 2 percentage can reach the surface of the Earth. UVB has a red spot effect on the body which can promote mineral metabolism and vitamin D formation in the body. However, too much UVB will lead to darken the skin and even red peeling. The band with the wavelength ranges from 200nm to ~280nm is designated as UVC. It has the worst penetrating ability among three ultraviolet, which cannot penetrate the cloud and barely reach the ground. UVC is very harmful to the human body. In a short time, it can burn the skin and in a long term or high intensity radiation will result in skin cancers. In addition, detectors have also made a rapid development in recent years. Thanks to the Einstein's explanation of the photoelectric effect, UV radiation signals can be transformed to electronic signals and can be measured easily by the detectors.

Contemporarily, ultraviolet photodetectors which use photoelectric effect to measure UV radiation device have a great number of applications [3-5]. For example, ultraviolet photodetectors can be used as one kind of communication techniques because of its high anti-interference in the military field and can be used to monitor and forecast of disaster weather. Moreover, it can be also used to monitor marine oil pollution due to the fluorescence effect in ultraviolet region. In biomedical domain, ultraviolet photodetectors can be used for various medical tests such as blood, microorganism and cancer cells. The detection results are not only intuitive but also accurate and fast. Nowadays, the research of the ultraviolet photodetectors is very popular. Ultraviolet photomultiplier and ultraviolet photodetectors based on Si have been widely used in many areas and wide bandgap ultraviolet photodetectors are research hotspot now, e.g., ultraviolet photodetectors based on TiO_2 or based on GaN. Although compared to the traditional photodetectors wide bandgap ultraviolet photodetectors have higher responsivity and sensitivity, it still faces some challenges today and the biggest problem is the quality of material. While improving the quality of materials, researchers are also trying to improve their photoelectric properties though different approaches, e.g., surface modification, material surface functionalization and doping and optimization of device structure [6].

The aim of this paper is to introduce the fundamental knowledge about ultraviolet photodetectors and summary the recent progress of UV photodetectors. The rest part of the paper is organized as follows. The Sec. 2 will introduce the principle and types of UV photodetectors. The Sec. 3 will demonstrate the components of photodetectors. Afterwards, the state-of-applications will be presented in the Sec. 4 and the corresponding limitations as well as future prospects will be pointed out accordingly in the Sec. 5. Eventually, a brief summary is given in Sec. 6.

2. Principle and types of ultraviolet photodetectors

2.1 The principle of ultraviolet photodetectors

Ultraviolet photodetectors convert light into electricity in the optical communication system, which is mainly based on the photovoltaic effect of the semiconductor material. In addition, the photovoltaic effect refers to the phenomenon that light causes a potential difference between heterogeneous semiconductors or between different parts of a semiconductor and a metal. Moreover, the working mechanism of ultraviolet photodetectors is about three steps: the first step is that photon-generated carriers are generated under illumination; the second step is that the carrier's diffusion or drift to form current; the last step is that the photocurrent is amplified and converted into voltage signals in the amplifier circuit. When the detector surface is illuminated by light, if the material bandgap width is less than the energy of incident light photon, i.e., valence band electrons can transit to the conduction band to form the photocurrent. Typically, ultraviolet photodetectors have five performance indexes to characterize. The first one is responsivity (R). The ratio of the photocurrent to the product of the illuminated light power, referring to Equation (1):

$$\boldsymbol{R} = \frac{\boldsymbol{I_p}}{\boldsymbol{P} \cdot \boldsymbol{S}} \qquad (1)$$

where, I_p is the magnitude of photocurrent, S is the area of light received and P is the power of light source. The responsivity of photodetector is higher, the efficient of converting from photons to electron hole pairs is higher and the performance of this photodetector is better. The second parameter is sensitivity (S). The ratio of the photocurrent minus the dark current to the dark current, referring to Equation (2):

$$\boldsymbol{S} = \frac{\boldsymbol{I_p} - \boldsymbol{I_{dark}}}{\boldsymbol{I_{dark}}} \qquad (2)$$

where I_{dark} is the magnitude of dark current. The third parameter is time response, which is corresponding to the speed of response of ultraviolet photodetectors to light signal. Response time has two parameters. The first one is τ_r, which describes the response time of increasing the photocurrent to 90% of the peak current. The second one is τ_d, which describes the response time of reducing the current to 1/e of the steady-state current. The next one is cut-off wavelength (λ_0), which is the longest wavelength that a photodetector can detect, as given in Equation (3):

$$\boldsymbol{\lambda_0 = \frac{hc}{E_g}} \quad (3)$$

Here, h is Planck's constant, c is the speed of light in the vacuum and E_g is the bandgap. The last term is the quantum efficiency (η). Every incident photon has the willing to create an electron hole pair. However, not all incident photons can be produced electron hole pairs, which means that the number of incident photons is more than the figure for electron hole pairs. The quantum efficiency can be calculated by the Equation (4).

$$\boldsymbol{\eta(\lambda) = R_\lambda \frac{hc}{q\lambda}} \quad (4)$$

where, R_λ is the responsivity of the wavelength λ and q is the electron charge.

2.2 The types of ultraviolet photodetectors

Usually, ultraviolet photodetectors fall into two categories: vacuum UV detectors and solid-state UV detectors [7]. The vacuum UV detectors are based on ultraviolet photomultiplier tubes, which have the advantages of good stability, quick response time, low dark current and high current gain. Although, this kind of UV detectors can achieve high response UV detection, it needs high power supply and the cathode refrigeration. Hence, it has many disadvantages such as high price, big power consumption and big volume.

Solid-state UV detectors are based on semiconductor materials. So far, researchers are focus on the wide bandgap UV detectors. Based on the structure of the wide bandgap UV detectors, it can be divided into two groups: photoconductivity detectors and photovoltaic detectors. Photovoltaic detectors can be also divided into metal-semiconductor-metal (MSM) structure detector, p-n junction and p-i-n junction detector, avalanche structure detector, Schottky barrier detector and heterojunction detector. Different kinds of UV detectors have different advantages as well as disadvantages, so it is necessary to choose the UV detector according to the usage conditions. Fig. 1 shows the different structures of wide bandgap UV detectors [7].

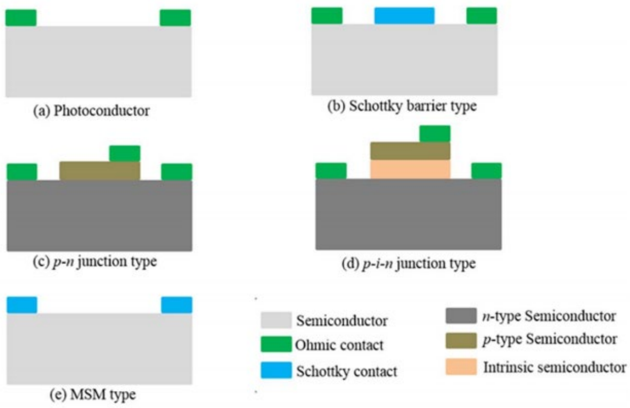

Figure 1. Schematic structures of different types of wide bandgap UV detectors [7].

3. Component of UV photodetectors

At present, ultraviolet photodetectors have been widely used in various fields. However, with the development of science and technology, all fields are not enough to meet the current ultraviolet photodetectors. Besides, the UV photodetectors with fast response speed, high sensitivity and good accuracy are urgent in need. Hence, the researchers focus their studies on the wide bandgap UV photodetectors based on different materials (e.g., TiO_2), which will be introduced respectively in the following part.

Titanium dioxide (TiO_2) is an environmentally friendly light conversion material, which has a unique absorption character of ultraviolet light. It is also an n-type semiconductor with a wide bandgap ranging from 3.0 to 3.2 eV for rutile and anatase, respectively. Due to its excellent chemical stability, non-toxicity and low cost, it has become an ideal material to build wide bandgap ultraviolet photodetectors. So far, many ultraviolet photodetectors based on with different modification methods have been reported and this kind of UV photodetectors would be reviewed in this section.

The first is self-powered UV photodetectors based on intrinsic of TiO_2. In this research field, most studies are used TiO_2 nanorods on account of the great electronic transmission capacity of nanostructure. Xie et al. fabricated a nanostructure self-powered quasi-solid UV photodetector, which is based on light trap structure embedded liquid (LC) crystal electrolyte [8]. In addition, vertical rutile type TiO_2 grows on FTO conductive glass. When the wavelength of 383nm UV light illuminates, the efficiency of photoelectric conversion up to 29% and the response time is less than 0.03 second. Sun et al. have reported Fe doped TiO_2 (Fe: TiO_2) ultraviolet photodetectors with fast response speed, high sensitivity and self-power and this modification method is called the self-powered UV photodetectors based on doping type [9]. Furthermore, the third is self-powered UV photodetectors based on modification of noble metal. Ferhati et al. have used the Grazing Angle deposition (GLAD) technology to prepare TiO_2/Ag/TiO_2 three thin films and analyzed this structure to get that when the deposition angle equal to 80 degrees, it can achieve the nearly perfect UV detection [10]. In addition, researchers also have reported the self-powered UV photodetectors based on TiO_2 heterojunction composite (e.g., NiO and MgO). As illustrated in the Fig 2., combining with TiO_x thin film, the NiO/TiO_x NRs heterojunctions have faster responsivity and better detection ability [11].

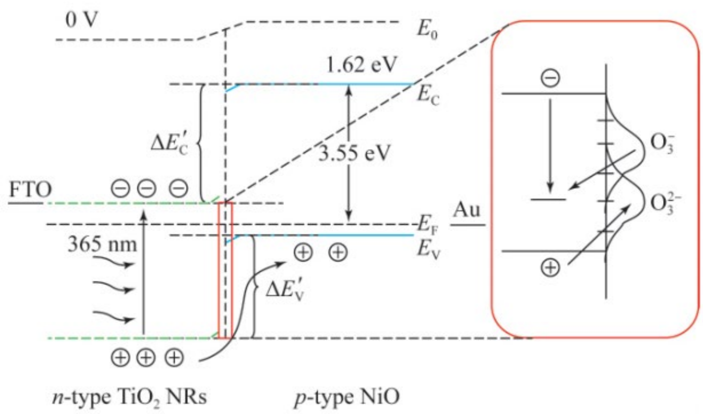

Figure 2. Structure and energy band diagram of NiO/TiO2 NRs heterojunctions under 0V [11].

Overall, although UV photodetectors based on TiO_2 have completed some substantial progress, it still faces many difficulties and problems, e.g., the composition of electrolyte and recombination of electrolyte with photogenerated electrons. In addition, the way to realize the stable operation of devices and how to design a reasonable device structure are still tough issues ought to be addressed. In the future, ultraviolet photodetectors based on TiO_2 are still research hotspots. If the difficulties can be tackled, wide bandgap UV photodetectors based on TiO_2 can be commercial to replace the ultraviolet photomultiplier tubes and photoconductivity detectors.

4. State-of-art applications

The way to effectively deal with high-rise building fire is an urgent case needed to be solved for the country and fire workers. From the angle of high-rise residential buildings, it is safer and less costly to shut down the risk of fire at the source of the fire disaster. A fire alarm is essential. Standard fire alarm devices on the market are red, purple, smoke, temperature, etc. Compared to the other two, UV fire alarm has miniaturization properties, low cost and high sensitivity.

Recently, researchers have shown an increased interest in an ultraviolet flame detector capable of timely and remote alarm and high accuracy of detection. This UV photocell has a high signal ratio, high reliability, very fast noise response and very low signal detection capability. On the other hand, the fire alarm is equipped with a SMS alarm module. Once the unknown fire source is found, the real-time surveillance situation will immediately be sent to his mobile number linked by Internet of Things technology. The response time is lower than 3 and timeliness is high.

The fire alarm consists of two parts: the flame detection module based on the R2868 UV light cell and the GSM SMS alarm module. Part of flame detection to complete the acquisition of flame signal, processing and response; The SMS alarm module recognizes response results and sends fire information to the customer via SMS. Among them, its flame detection module uses a violet external sensor that is insensitive to visible light, and the effective wavelength of the measurement is 185-260 nm [7-8]. Unlike solid state detectors, UV detectors do not need optical filters, making them easy to operate and suitable for flame detectors and fire alarms.

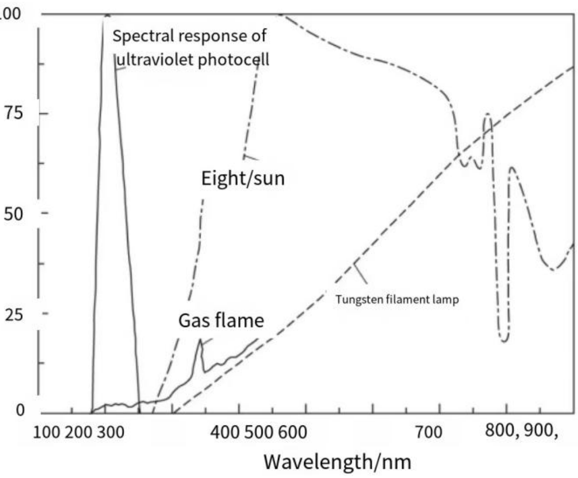

Figure 3. UV spectral response curve [12].

UV light cells consist of a quartz glass tube containing two electrodes. Metal materials that form the cathode are only sensitive to UV light and emit photoelectrons when exposed to UV light. R2868 only responds to the purple outer line, which has a special wavelength of 185 ~ 260nm in the flame, and is not sensitive to other ultraviolet rays in the natural light source. When the tube is not radiated from the purple external line, the resistance value between the cathode and the cathode tends to be infinite. It doesn't have a photocurrent. The UV spectral response curve is exhibited in Fig. 3.

Under the action of an external electric pressure, the electrons emitted by the cathode move towards the anode at high velocity. During motion, the photoelectrons collide with the body of the gas in the pipe, making it electrically separated into positive and negative ions. The negative ions are then electrically separated from other gas molecules under the action of the electric field. Therefore, the cycle is rapidly repulsed by a large number of photoelectrons and ions between the anode and cathode, presenting a conduction state. At that moment, a pulse signal is generated in the circuit, and the entire system responds rapidly with that pulse signal.

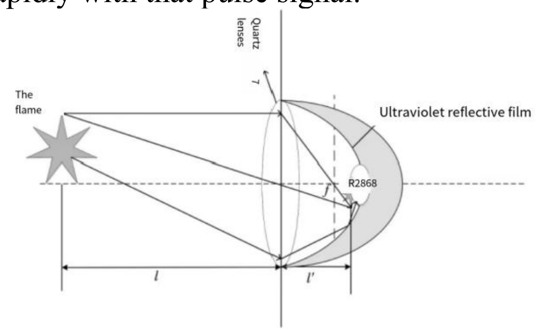

Figure 4. The schematic diagram of front-optical structure [14].

In addition, the flame detection module can also use the optical front window structure, as shown in the design of the optical front window structure (Fig. 4). The objective lens adopts UV furnace quartz lens, which can converge the emission and astigmatism at the edge of the field of view to the receiving end of the light sensitive tube, and increase the light energy received by the sensor. Simultaneously, the inner wall of the front window is coated with ultraviolet reflection film, and the non-paraxial light incident on the inner wall of the front window is reflected by the purple external reflection film.

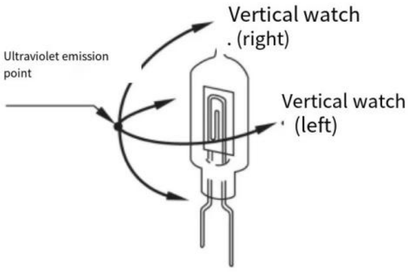

Figure 5. Schematic diagram of observation [12].

Converging to the receiving surface of the sensor improves the sensitivity of detection and environmental adaptability. Compared to other types of UV phototubes, the selected R2868 UV on/off Hamamatsu detector has high sensitivity, short reaction time, and is not as expensive as PMT tubes. Compared with other types of flame detection technology, its passive detection characteristics make the signal-to-noise ratio is very high and the reliability is stronger because it does not need to emit electromagnetic signals. Besides, it can cover almost the entire viewing angle, and suited to his work in a wide range of temperature, high usability. A sketch of the diagram of observations is given in Fig. 5.

In parallel, ultraviolet detectors are also used extensively in the detection of nuclear radiation. In nuclear radiation detection applications, semiconductor detectors have the characteristics of high sensitivity, high energy resolution, small size, easy integration, high spatial resolution, fast response speed and wide linear range, etc., which have attracted attention in nuclear radiation monitoring, high energy physics reaction products inspection and aerospace and other fields.

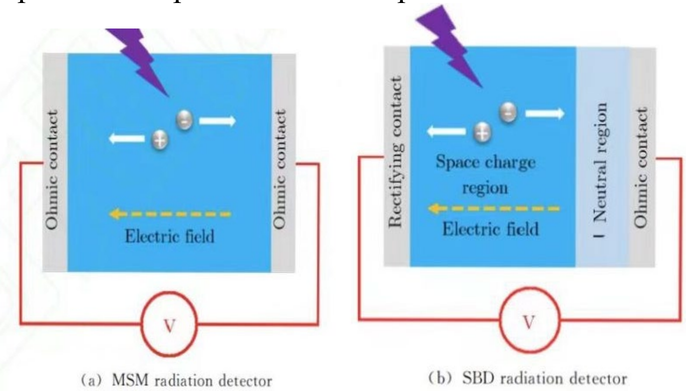

Figure 6. Working models pf two different structures of Ga_2O_3 semiconductor nuclear radiation detectors [15].

The nuclear radiation detector is a kind of converter which converts neutrons, γ-rays, X-rays and charged particles into visible signals through the interaction between radiation and matter. The development of a semiconductor nuclear radiation detector in the field of nuclear detection involves improving its own material properties and innovating application scenes. Fig. 6 shows the working model of Ga2O3 semiconductor nuclear radiation detector based on two different structures, i.e., the high-resistance device based on the compensation high-resistance material of gold semi-guide metal structure, and the Schottky junction device based on Schottky diode structure. The high resistance semi-guide sensor is suitable for the detection of high energy lines and particles. The junction type device is easy to adjust the thickness of the sensitive region, and the electric field intensity in the sensitive region is larger, the charge collection efficiency is higher, and the linear output characteristic is good, suitable for α particles and other heavy charge particles detection and mixing field measurement. The Schottky junction device may set a higher electric field strength, but the output voltage wave of the electric source has a great influence on the output of the signal. Ga2O3 semiconductor nuclear radiation detector research is still in the initial stage, mainly reflected in the device type, device nuclear radiation response performance The quantitative and qualitative study of the correlation between the unsatisfactory and the electrical properties of devices and material defects is relatively lacking in two aspects. Nuclear radiation of the device concerned. The stress mechanism, the influencing factors of radiation-induced non-equilibrium carrier transport and the law and characteristics of nuclear radiation response need further study.

5. Limitations and Future prospects

There are two main kinds of limitations of state-of-art ultraviolet detectors. The first one is the performance issue. The working capability usually decides the maximum application range of one detector and is the top consideration for most users. The ultraviolet detector has its own drawback, e.g., material quality problems, stability of long-term operation, reliability in complex and harsh conditions, and the average lifetime. These performance issues impede the ultraviolet detectors in further development. The second one is the economic limitation. In order to match the requirement, the high-performance ultraviolet detectors are often manufactured with uncommon-used materials, or commonly-used materials subject to unique processes, which would definitely increase the total cost and lower the productivity. It is a critical reason for unpopular in some low-profit areas.

Compared with microwave detection and infrared detection, ultraviolet detectors have advantages in working in a strong electromagnetic radiation environment and are less susceptible to long-wave electromagnetic interference. Therefore, the UV detector has broad development prospects in both military and civilization. In the military aspect, for instance, the UV detectors could be used in high confidentiality communication and early warning and tracking system of missiles. UV detectors also have been widely used in civilization, which includes astronomy, disaster forecasting, fire alarm, marine oil pollution monitoring, biomedical and more. With the improvement of technology, the applications of the new generation of UV detectors would be greatly expanded in the future.

6. Conclusions

In summary, this paper discusses the perspective of the definition, current development, principle, common types, and some applications of ultraviolet photodetectors. The ultraviolet photodetectors are generally divided into two types: vacuum UV detectors and solid-state UV detectors. Nowadays, the wide bandgap UV photodetectors which are based on different materials (e.g., TiO_2) have become a new focus for many researchers. If their difficulties and drawbacks could be solved, wide bandgap UV photodetectors based on TiO_2 are able to replace the ultraviolet photomultiplier tubes and photoconductivity detectors due to fast response speed, high sensitivity, self-power, and other advantages. In addition, we also introduce the UV photodetector’s applications in fire alarm and nuclear detection and how they benefit people’s lives and promote relevant study processes. In the future, with the new generation UV photodetectors coming out, we may be able to use them in more relevant applications with better performance and create great development in daily life. Overall, these results offer a guideline for the direction of future development of UV photodetectors.

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